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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PERFORMANCE EVALUATION  
OF A  
LIQUID-SHROUDED CRYOGENIC STORAGE SYSTEM

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AUTHOR: Pat B. McLaughlan



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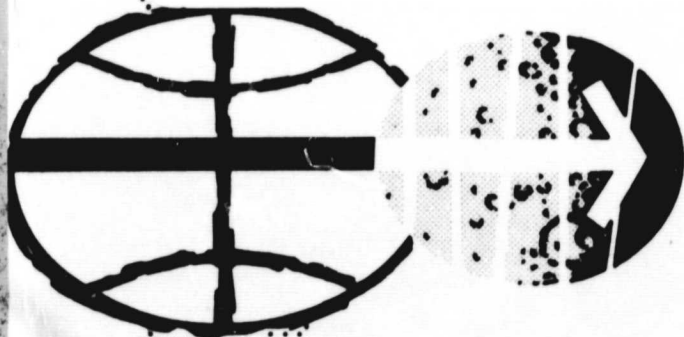
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PREPARED BY:	Pat B. McLaughlan	<i>Pat B. McLaughlan</i>
APPROVED BY:	(SECTION) Clarence E. Propp	<i>Clarence E. Propp</i>
APPROVED BY:	(BRANCH OFFICE) Allen H. Watkins	<i>Allen H. Watkins</i>
APPROVED BY:	(DIVISION) Joseph G. Thibodaux	<i>Richard B. Ferguson for JGT</i>
APPROVED BY:		

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## INTRODUCTION

The liquid-shrouded Cryogenic Storage System (CSS) was developed by the Instruments and Life Support Division of the Bendix Corporation as a potential means of satisfying the cryogenic storage requirements imposed by long duration missions. It was procured by NASA/MSC under contract NAS 9-4643.

The primary objective of this test program was to evaluate a cryogenic liquid shroud as a means of thermal insulation for a primary cryogenic fluid contained in a pressure vessel. This information was required in order to establish feasibility of the concept in designing an alternate LM helium pressurization system. The thermal performance evaluation of the CSS consisted of evaporation rate tests, nonvented standby tests, and minimum flowrate tests. For the first series of tests, liquid nitrogen was used as the shroud fluid and liquid oxygen as the primary stored cryogen. For the second series of tests, liquid hydrogen was used as the shroud fluid and helium as the primary cryogen.

Although the concept of insulating a primary cryogenic liquid by vaporization of an intermediate cryogenic liquid in a shroud had been used extensively in laboratory helium dewars, there had been little work in using either integral or separate shroud cooling for spacecraft applications. Preliminary examination indicated potential advantages of the shroud concept for flight cryogenic storage systems.

A design with a separate or isothermally mounted shroud, such as used in a standard liquid nitrogen shrouded helium dewar, essentially provides a controlled temperature environment for the pressure vessel contents by vaporization cooling of the shroud fluid. However, for the integral shroud design as used in the Bendix CSS, the pressure vessel wall is common to both the pressure vessel and shroud fluids and is not separated by a vacuum as in the isothermal shroud design.

The test was conducted in the Power Systems Test Facility, building 354, Thermochemical Test Branch, for the Power Generation Branch of the Propulsion and Power Division. The CSS was delivered to MSC on November 20, 1966, and the test program was accomplished from December 8, 1966, to February 21, 1967.

## TEST ARTICLE DESCRIPTION

The liquid-shrouded CSS consists of an inner pressure vessel surrounded by, and permanently attached to, an integral shroud vessel. The shroud and pressure vessel assembly is supported in the outer shell by six radial bumpers. Between the outer shell and the shroud a high vacuum is maintained to eliminate convective heat leak. An isothermal, vapor-cooled, discrete radiation shield located in the vacuum annulus surrounds the shroud. Vented cryogen from the shroud can be directed through the vapor cooling tube on the radiation shield to further reduce radiant heat leak. Figure 1 illustrates the internal construction of the CSS.

The weight of the dry CSS without external components is 76.6 pounds and the weight of the total dry system including external components is 109.3 pounds. The inner pressure vessel has a diameter of 17.440 inches, a usable volume of 1.60 cubic feet, and an annealed Inconel 718 wall 0.145 inches thick. The operating pressure is 1000 psig and the proof pressure is 1400 psig. Located within the pressure vessel are an antistratification motor-fan, a 171-watt internal heater, a capacitance-type quantity sensor, and a copper-constantan thermocouple. The antistratification motor-fan and the heater may be automatically operated by a pressure switch or manually controlled from a control panel provided with the system.

The shroud vessel material is also annealed Inconel 718. The shroud has an inner diameter of 18.99 inches, a wall thickness of 0.030 inches, and a usable volume of 0.382 cubic feet. The operating pressure is 25 psig and the proof pressure is 40 psig.

The vapor-cooled discrete shield is 6061-0 aluminum. The shield inner diameter is 21.090 inches and the wall thickness is 0.020 inches. The annealed copper vapor cooling tube attached to the shield has a 0.250-inch diameter, a 0.030-inch wall thickness, and is 31 feet long. The outer shell material is 304L stainless steel with an inner diameter of 22.000 inches and a 0.030-inch wall.

Fill, vent, and relief valves for the pressure vessel and shroud were supplied with the system. Two vent valves for the shroud vessel permit either normal shroud venting or vapor cooling of the discrete radiation shield. The external components are located on the mounting carriage. An ion pump attached to the evacuation tube of the CSS vacuum annulus is provided for two purposes: (1) to remove outgassed materials from the vacuum annulus and (2) to provide a means for determining the pressure within the vacuum annulus. The ion pump operates from a separate power supply provided with the system.

The mounting carriage supports the outer shell at the points of contact between the radial bumpers and outer shell so that all vessel loads are carried directly from the bumpers through the outer shell and into the mount carriage. The system is supported at three vibration damping locations. Figure 2 illustrates the liquid shrouded CSS in the support fixture.

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## TEST PROGRAM

Nine individual tests were conducted to determine the thermal performance of the CSS. Tests 1 and 2 were liquid nitrogen evaporation rate tests of the shroud to evaluate shroud thermal performance. Tests 3 and 4 were thermal performance evaluations of the pressure vessel with liquid oxygen. Tests 5 and 6 were liquid hydrogen evaporation rate tests of the shroud to evaluate shroud thermal performance. Tests 7 and 8 were thermal performance evaluations of the pressure vessel with helium. Test 9 was an additional nonvented standby test of the pressure vessel with helium as the primary cryogen and liquid hydrogen in the shroud. A maximum shroud fill was maintained throughout test 9. The following table is a summation of the tests.

Test no.	Fluids		Remarks
	Shroud	Pressure vessel	
1	Liquid nitrogen	Empty	Shroud evaporation rate test with no vapor cooling
2	Liquid nitrogen	Empty	Shroud evaporation rate test with vapor cooling
3	Liquid nitrogen	Liquid oxygen	Shroud evaporation rate test with vapor cooling; pressure vessel nonvented standby test
4	Empty	Liquid oxygen	Pressure vessel minimum flow rate test
5	Liquid hydrogen	Empty	Shroud evaporation rate test with no vapor cooling
6	Liquid hydrogen	Empty	Shroud evaporation rate test with vapor cooling
7	Liquid hydrogen	Helium	Shroud evaporation rate test with vapor cooling; pressure vessel nonvented standby test
8	Empty	Helium	Pressure vessel minimum flow rate test
9	Maximum fill of liquid hydrogen	Helium	Shroud evaporation rate test with vapor cooling; pressure vessel nonvented standby test

## TEST PROCEDURE

Variations in thermal performance were prevented by maintaining a constant 70° F environment. Heater operation was controlled automatically by a facility temperature controller and a thermocouple temperature sensor located inside the fixture. An alternate temperature control was manual adjustment of the heater voltage to provide the required heater power to maintain a constant interior temperature. The constant-temperature enclosure is shown in figure 3.

Safety precautions included a hydrogen detector located in the test enclosure which actuated a control room alarm if hydrogen concentration reached 10 percent of the lower explosive limit and a gaseous nitrogen system to minimize the possibility of forming a combustible mixture in the event of a hydrogen leak into the enclosure.

To support the CSS operation, a gas flow panel was fabricated to house fluid control components and instrumentation. A schematic representation of the CSS and fluid flow panel is shown in figure 4.

The following parameters were recorded by a digital data acquisition system throughout the test program: shroud pressure; pressure vessel pressure; pressure vessel fluid temperature; pressure vessel fluid density (capacitance); shroud and pressure vessel flowrates; the top, girth, and bottom CSS outer shell temperatures; and the environmental temperature.

Shroud and primary cryogen pressures were measured by strain gage pressure transducers, the primary cryogen fluid temperature by thermocouples, the fluid density by capacitance readings of the quantity gaging system, and the outer shell and environmental temperatures by platinum resistance temperature transducers. The shroud and pressure vessel fluid flowrates were measured by thermal mass flowmeters and wet test flowmeters. The thermal mass flowmeter readings were used as the primary flow measurement device throughout the test program, primarily because the thermal mass flowmeter is not substantially affected by minor changes in gas temperature and pressure, and also because more adequate calibration techniques are available for this type of flowmeter. The flow points shown on all curves were based on mass flowmeter data. Figure 5 is a block diagram of the instrumentation system.

The test fixture was located on a weighing system platform which provided total fluid weight data. Pressure vessel fluid densities were based on the weighing system data. Redundant density data was provided by the quantity gaging system. The photograph of the test setup, shown in figure 6, shows the weighing system, the temperature control enclosure, the gas flow panel, and the wet test flowmeters.

The pressure vessel was proof pressurized with gaseous nitrogen prior to test 1. The shroud was not proof tested because of its low pressure operation.

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The liquid oxygen, nitrogen, and hydrogen used throughout this test program were transferred to the test article from facility storage dewars. A foam insulated 1/2-inch diameter transfer line was used for liquid nitrogen and oxygen transfers. A vacuum insulated 1/4-inch diameter transfer line was used for the liquid hydrogen transfer. Each cryogen was transferred through a 25-micron (absolute) filter to minimize particulate contamination. When helium was used as the test fluid, it was filtered, precooled through a nitrogen bath, and then cooled to liquid hydrogen temperature.

The pressure vessel nonvented standby test consisted of filling the pressure vessel to a high percentage fill. Then all vent paths were blocked and a pressure increase resulted from the ambient heat leak. The nonvented standby time was the time required for the CSS pressure to increase from initial to maximum operating pressure with no heater operation. For the shroud evaporation rate test, the cryogen in the CSS shroud was allowed to boil at atmospheric pressure and vent to the atmosphere with no attempt to control the flowrate from the CSS. The flowrate was determined by the fluid evaporation rate. For the minimum flowrate test, the flowrate from the pressurized primary cryogen was controlled manually by metering valves to hold a constant operating pressure. The fluid expelled is a function of the heat leak for a given fluid density. The fluid density range through which the test was conducted included the region of minimum specific energy required to expel a unit mass of oxygen (minimum  $dQ/dm$ ).

## RESULTS AND DISCUSSIONS

The pressure vessel was successfully proof pressurized on December 8 with gaseous nitrogen to 1300 psig and the pressure was maintained for a 5-minute period. The initial fill of the shroud with liquid nitrogen was completed on December 9. The shroud vented until December 12 when additional liquid nitrogen was added to achieve a maximum fill. The liquid nitrogen capacity of the shroud based on a maximum fill was 19.3 pounds. The 3-day liquid nitrogen soak period ensured thermal stabilization of the CSS.

Test 1 - Shroud Nitrogen Evaporation  
Rate Test Without Vapor Cooling

The shroud was filled with liquid nitrogen and the pressure vessel with gaseous nitrogen at a lower pressure than the shroud. The test ran for 60 hours. During the 45- to 55-hours elapsed time (E.T.) period, the environmental temperature averaged 70.5° F and the average of the three outer shell temperatures was 68.1° F. The hourly evaporation rate for this period averaged 0.114 lb/hr. The average evaporation rate over the whole test was 0.113 lb/hr based on the indicated fluid weight change. The average heat leak for the test was 9.79 Btu/hr. The average shroud pressure for the 45- to 55-hours E.T. period was 1.76 psig.

Test 2 - Shroud Liquid Nitrogen  
Evaporation Rate Test With Vapor Cooling

Test 2 followed test 1 without additional liquid nitrogen being added to the shroud. However, the shroud vent gas path was changed to pass through the vapor-cooled shield. The duration of test 2 was 53 hours. The environmental temperature averaged 70.2° F and the average of the three outer shell temperatures was 67.6° F.

The 35- to 45-hours E.T. period indicated the most stable flowrate for this test. The average evaporation rate for this period was 0.104 lb/hr and the average shroud pressure was 1.01 psig. The average heat leak was 8.87 Btu/hr. Vapor cooling of the radiation shield resulted in a 9.4 percent improvement in heat leak for test 2 over test 1. Figure 7 illustrates the nitrogen evaporation rate from the shroud for tests 1 and 2.

Test 3 - Pressure Vessel Oxygen Nonvented Standby Performance  
and Shroud Nitrogen Evaporation Rate with Vapor Cooling

The primary objective of this phase of the test was to determine CSS thermal performance based on an oxygen nonvented standby test of the pressure vessel. Another objective was to determine shroud thermal performance with the pressure vessel filled. The shroud liquid (nitrogen) surrounded the pressure vessel

(containing liquid oxygen) and the shroud fluid was vented to the atmosphere causing the shroud liquid nitrogen to cool the higher boiling point liquid oxygen ( $-297^{\circ}\text{F}$ ) to near the temperature of boiling liquid nitrogen ( $-320^{\circ}\text{F}$ ). At that point the oxygen was in a two-phase, liquid/vapor state and the pressure decreased to the new equilibrium corresponding to  $-320^{\circ}\text{F}$ . To increase the oxygen density, the pressure vessel was pressurized from an external source of gaseous oxygen. The pressurization caused the fluid to enter the compressed liquid region. The process was essentially a constant temperature pressurization since the fluid density was increased by the addition of mass and the oxygen was cooled by liquid nitrogen. Following gas pressurization to the desired density and pressure, the high density subcooled oxygen in the pressure vessel was maintained in a nonvented standby condition while the shroud liquid nitrogen was vented at atmospheric pressure. The heat leak to the pressure vessel was then determined by the oxygen rate of pressurization.

The shroud nitrogen was refilled to ensure maximum fill for this test. A 21-hour period was required to achieve a thermally stable system while pressurizing the pressure vessel liquid oxygen with oxygen gas. An extended amount of time was required to thermally equalize the oxygen during the period of external gas pressurization because the CSS antistratification fan motor was inoperative.

The pressure vessel oxygen required 100 hours for a pressure increase from 459 to 935 psig. Following the liquid nitrogen addition at 0 hour E.T., the shroud flow increased until a flow-pressure equilibrium was achieved. The shroud flow then continuously decreased throughout the test. The shroud evaporation rate was based on an hourly average from 15 to 100 hours E.T. During this period the average environmental temperature was  $70.0^{\circ}\text{F}$  and the average outer shell temperature was  $66.7^{\circ}\text{F}$ . The average evaporation rate was 0.121 lb/hr. The average shroud pressure was 1.12 psig. The resultant shroud heat leak for test 3 was 10.3 Btu/hr. Figure 8 illustrates the shroud nitrogen evaporation rate and the nonvented standby pressurization rate of the pressure vessel oxygen for test 3. The nonlinear pressure rise of the oxygen was apparently caused by the decreasing shroud liquid nitrogen level.

The oxygen fill density for test 3 was  $74.2\text{ lb/ft}^3$ . This figure is based on a fluid weight of 118.1 pounds of oxygen obtained immediately following test 3 when the remaining liquid nitrogen in the shroud was expelled. The normal boiling point liquid oxygen density  $71.3\text{ lb/ft}^3$ . Pressurization from an external source and cooling the oxygen to liquid nitrogen temperature caused the higher fluid density. Because the pressure vessel fluid was slightly warmer than the fluid, however, the indicated fluid density,  $74.2\text{ lb/ft}^3$ , was lower than the theoretical value,  $75.1\text{ lb/ft}^3$ , based on  $140^{\circ}\text{R}$  and 459 psia.

Based on the measured density of  $74.2\text{ lb/ft}^3$ , the heat leak to the vessel was calculated from the changes in internal energy of the fluid. For the period from 0 through 60 hours E.T. the average heat leak was 0.402 Btu/hr and for the 60- to 100-hour E.T. period, the average heat leak was 1.16 Btu/hr. The higher heat leak experienced during this later period indicated a reduction of pressure vessel thermal performance as the shroud liquid level decreased. The average pressure vessel heat leak over the entire nonvented standby test (0 to 100 hours E.T.) was 0.706 Btu/hr.

Test 4 - Pressure Vessel Oxygen Minimum Flowrate  
Test With Shroud Empty

The pressure vessel oxygen minimum flowrate test (equilibrium flowrate test) was initiated 7 hours after the completion of test 3. The 7-hour interval was required to complete pressurization to 950 psig, to discharge the remaining nitrogen from the shroud, and to establish an oxygen flowrate from the pressure vessel. A constant 950 psig was maintained throughout the test by manual adjustment of the oxygen discharge metering valve. Test 4 was conducted over two different fluid density ranges. Test 4.a was at the maximum density and test 4.b was at the fluid density corresponding to the minimum  $dQ/dm$  point.

Test 4.a was conducted for 78 hours E.T. over a fluid density range from  $74.1 \text{ lb/ft}^3$  to  $69.9 \text{ lb/ft}^3$ . The environmental temperatures for test 4.a averaged  $70.2^\circ \text{ F}$  and the average of the three outer shell temperatures for the test was  $67.3^\circ \text{ F}$ . The average of the hourly flowrates for this period was  $0.060 \text{ lb/hr}$ . The average heat leak was  $9.96 \text{ Btu/hr}$  based on a flowrate of  $0.060 \text{ lb/hr}$  and an average density of  $71.8 \text{ lb/ft}^3$  at 950 psig.

Test 4.b required repressurization of the pressure vessel oxygen following depletion of the oxygen to a total fluid weight of 55 pounds. The pressure vessel oxygen was repressurized with the CSS internal heaters (1.99 amps and 120 volts) from 5 to 941 psig in 3 hours 39 minutes. Following the oxygen repressurization, a continual pressure decay was experienced. The CSS was repressurized to 950 psig with the heaters several times, but the pressure decay resumed after heater cutoff at a rate of approximately  $45 \text{ psi/hr}$ . The pressure vessel oxygen was then completely discharged to verify the weigh system performance. Following a calibration of the weigh system which verified the previous fluid density values, liquid oxygen was added to the pressure vessel for a system fluid density of  $35 \text{ lb/ft}^3$ . The heaters were actuated and the oxygen was pressurized to 950 psig in 2.0 hours. A pressure decay of  $76 \text{ psi/hr}$  was experienced following heater deactivation. Since the internal antistratification fan was inoperative and the CSS pressure vessel contained no other means for preventing thermal stratification, operation of the heaters probably caused severe thermal stratification. The pressure continued to decay as the thermally stratified fluid approached thermal equilibrium. The system was thoroughly leak checked on numerous occasions to ensure that leakage was not the cause of this pressure decay. An attempt to partially relieve the stratification consisted of rocking the CSS and test fixture from side to side for approximately 5 minutes. A significant pressure decrease was experienced: before fluid agitation, oxygen pressure = 920 psig and oxygen temperature =  $-162^\circ \text{ F}$ ; after fluid agitation, oxygen pressure = 562 psig and oxygen temperature =  $-191^\circ \text{ F}$ . The fluid was pressurized and agitated several times with minor pressure decays occurring for 15 hours until thermal equilibrium was achieved and a pressure increase was experienced in the nonvented condition..

Test 4.b was conducted for 23 hours over a fluid density range from  $36.2 \text{ lb/ft}^3$  to  $33.4 \text{ lb/ft}^3$ . The average of the hourly flowrates for this period was  $0.175 \text{ lb/hr}$ . Based on an average fluid density of  $34.85 \text{ lb/ft}^3$  at 950 psig, the resultant heat leak was  $7.53 \text{ Btu/hr}$ .

Test 5 - Shroud Hydrogen Evaporation Rate  
Test Without Vapor Cooling

On January 30 the shroud was filled slowly to allow maximum fill and thermal stabilization. The liquid hydrogen capacity of the shroud, based on a maximum fill, was 1.69 pounds. For test 5, the shroud hydrogen vented directly through the shroud vent and did not make use of vapor cooling of the radiation shield. The pressure vessel contained only low pressure gaseous helium during both tests 5 and 6.

Test 5 ran for 31 hours. A slight decrease in flowrate started at 11 hours E.T. and continued until 26 hours E.T. when the vent rate started to decrease more sharply, indicating that the shroud was nearly empty. Figure 9 illustrates the evaporation rate versus E.T. for test 5. During the 10- to 20-hours E.T. period the evaporation rate was relatively stable. The environmental temperature averaged 70.4° F and the average of the three outer shell temperatures was 70.1° F. The average evaporation rate was 0.0451 lb/hr. The average shroud pressure was 2.28 psig and the resultant heat leak was 8.60 Btu/hr.

Test 6 - Shroud Hydrogen Evaporation Rate  
With Vapor Cooling

The shroud was refilled with liquid hydrogen immediately following test 5. Since test 6 started immediately following the addition of liquid hydrogen, a higher evaporation rate was indicated for the first 4 hours until a flow pressure equilibrium was established. For this test, the shroud hydrogen vent gas passed through the vapor cooled radiation shield. The duration of the test was 50 hours. Figure 9 illustrates the hydrogen evaporation rate during this test. The 33- to 43-hours E.T. period indicated the most stable evaporation rate for the test. At 44 hours E.T. evaporation rate indicated a decrease which continued for the remainder of the test. The environmental temperature for the 33- to 43-hours E.T. period averaged 70.3° F and the average of the three outer shell temperatures was 66.5° F. The average evaporation rate was 0.0267 lb/hr and the average shroud pressure was 0.89 psig. The resultant heat leak for test 6 was 5.11 Btu/hr. The vapor cooling of the radiation shield resulted in a 40.6 percent improvement in heat leak for test 6 as compared to test 5.

Test 7 - Pressure Vessel Helium Nonvented Standby Performance and  
Shroud Hydrogen Evaporation Rate With Vapor Cooling

The helium evaluation of the CSS consisted of pressurizing the CSS pressure vessel to 500 psig with gaseous helium while the CSS shroud contained liquid hydrogen. The liquid hydrogen shroud caused the gaseous helium temperature to stabilize slightly above -423° F (liquid hydrogen boiling point). The helium in the pressure vessel was placed on nonvented standby while the liquid hydrogen shroud vented to atmosphere. The thermal performance of the pressure vessel was then based on the nonvented standby time from 500 to 950 psig.

The helium fill density at 0 hours E.T. (1700 hours on February 8) was 4.38 lb/ft<sup>3</sup>. A relatively stable hydrogen evaporation rate from the shroud was maintained from 6 through 33 hours E.T. The environmental temperature for this period averaged 70.2° F and the average of the three outer shell temperatures was 64.9° F. The average shroud evaporation rate was 0.0345 lb/hr. The average shroud pressure for this period was 1.35 psig. Therefore, the average shroud heat leak for this period was 6.59 Btu/hr. A shroud hydrogen evaporation rate of approximately 0.018 lb/hr was experienced from 33 to 41 hours E.T. By 41 hours E.T., the hydrogen shroud flowrate was low (0.015 lb/hr) indicating that the shroud was essentially empty. At 45 hours E.T. the shroud vent was closed to prevent atmospheric contamination of the shroud.

The hydrogen filled shroud had a greater heat leak during this test than in the previous test with an empty pressure vessel (test 6). A similar increase in the nitrogen shroud heat leak occurred for the oxygen nonvented standby test (test 3) as compared to the nitrogen shroud evaluation with an empty pressure vessel (test 2). The reason for this higher heat leak could not be determined from test data. It is recommended that this phenomenon be investigated in future liquid shrouded CSS tests.

A period of decreasing helium pressure was experienced from 15 to 20 hours E.T. (495 to 489 psig). This pressure decay was attributed to a minor leak which was located and repaired. The period of decreasing pressure due to leakage was disregarded for calculation of helium pressurization rates. The following pressurization rates were recorded: 465 to 495 psig (0 to 15 hours E.T.), and 489 to 529 psig (20 to 33 hours E.T.). This resulted in a 70 psig increase in 28 hours E.T. or 2.5 psi/hr. After 33 hours E.T. when the shroud hydrogen evaporation rate was very low, the helium pressure increased from 530 to 610 psig (at 41 hours E.T.) for a pressurization rate of 10.7 psi/hr. The helium pressurization rate from 40 through 54.4 hours E.T. (610 to 934 psig) with no hydrogen flow from the shroud was 24.9 psi/hr.

The nonlinear pressurization rate during this test was apparently due to the depletion of the shroud liquid hydrogen. The pressure vessel heat leak from 0 through 33 hours E.T. (excluding the 5-hour period when the vessel was leaking) was 0.80 Btu/hr. The heat leak for the 33- to 41-hour E.T. period was 3.3 Btu/hr. The higher heat leak for this period again illustrates pressure vessel performance as a function of the shroud liquid level. The pressure vessel heat leak for the 41- to 54-hour E.T. period with no liquid hydrogen in the shroud was 8.1 Btu/hr. Figure 10 illustrates the shroud hydrogen evaporation and pressure vessel helium pressurization rates.

#### Test 8 - Pressure Vessel Helium Minimum Flowrate Test With Shroud Empty

The pressure vessel helium minimum flowrate test (equilibrium flowrate test) was initiated immediately following test 7. Because the hydrogen shroud had depleted 13 hours prior to the completion of test 7, it was not necessary to discharge the shroud fluid. A constant 950 psig helium pressure was maintained throughout the test by manual adjustment of the helium discharge metering valve. The helium fluid density ranged from 4.38 lb/ft<sup>3</sup> at 0 hours E.T. to 0.90 lb/ft<sup>3</sup>

The helium fill density at 0 hours E.T. (1700 hours on February 8) was 4.38 lb/ft<sup>3</sup>. A relatively stable hydrogen evaporation rate from the shroud was maintained from 6 through 33 hours E.T. The environmental temperature for this period averaged 70.2° F and the average of the three outer shell temperatures was 64.9° F. The average shroud evaporation rate was 0.0345 lb/hr. The average shroud pressure for this period was 1.35 psig. Therefore, the average shroud heat leak for this period was 6.59 Btu/hr. A shroud hydrogen evaporation rate of approximately 0.018 lb/hr was experienced from 33 to 41 hours E.T. By 41 hours E.T., the hydrogen shroud flowrate was low (0.015 lb/hr) indicating that the shroud was essentially empty. At 45 hours E.T. the shroud vent was closed to prevent atmospheric contamination of the shroud.

The hydrogen filled shroud had a greater heat leak during this test than in the previous test with an empty pressure vessel (test 6). A similar increase in the nitrogen shroud heat leak occurred for the oxygen nonvented standby test (test 3) as compared to the nitrogen shroud evaluation with an empty pressure vessel (test 2). The reason for this higher heat leak could not be determined from test data. It is recommended that this phenomenon be investigated in future liquid shrouded CSS tests.

A period of decreasing helium pressure was experienced from 15 to 20 hours E.T. (495 to 489 psig). This pressure decay was attributed to a minor leak which was located and repaired. The period of decreasing pressure due to leakage was disregarded for calculation of helium pressurization rates. The following pressurization rates were recorded: 465 to 495 psig (0 to 15 hours E.T.), and 489 to 529 psig (20 to 33 hours E.T.). This resulted in a 70 psig increase in 28 hours E.T. or 2.5 psi/hr. After 33 hours E.T. when the shroud hydrogen evaporation rate was very low, the helium pressure increased from 530 to 610 psig (at 41 hours E.T.) for a pressurization rate of 10.7 psi/hr. The helium pressurization rate from 40 through 54.4 hours E.T. (610 to 934 psig) with no hydrogen flow from the shroud was 24.9 psi/hr.

The nonlinear pressurization rate during this test was apparently due to the depletion of the shroud liquid hydrogen. The pressure vessel heat leak from 0 through 33 hours E.T. (excluding the 5-hour period when the vessel was leaking) was 0.80 Btu/hr. The heat leak for the 33- to 41-hour E.T. period was 3.3 Btu/hr. The higher heat leak for this period again illustrates pressure vessel performance as a function of the shroud liquid level. The pressure vessel heat leak for the 41- to 54-hour E.T. period with no liquid hydrogen in the shroud was 8.1 Btu/hr. Figure 10 illustrates the shroud hydrogen evaporation and pressure vessel helium pressurization rates.

#### Test 8 - Pressure Vessel Helium Minimum Flowrate Test With Shroud Empty

The pressure vessel helium minimum flowrate test (equilibrium flowrate test) was initiated immediately following test 7. Because the hydrogen shroud had depleted 13 hours prior to the completion of test 7, it was not necessary to discharge the shroud fluid. A constant 950 psig helium pressure was maintained throughout the test by manual adjustment of the helium discharge metering valve. The helium fluid density ranged from 4.38 lb/ft<sup>3</sup> at 0 hours E.T. to 0.90 lb/ft<sup>3</sup>

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at 106 hours E.T. The environmental temperature for the test period averaged 70.0° F and the average of the three outer shell temperatures for the test was 67.0° F.

Figure 11 charts minimum flow against fluid density for test 8. Each data point is an average of six of the hourly flowrate and fluid density readings. The helium fluid densities were based on helium temperature-pressure relationships. The data point scatter may have been caused by drifting in the pressure instrumentation and subsequent errors in manual flow correction. The heat leaks for test 8 were calculated from flowrates and their corresponding densities taken from figure 11.

Test 8 heat leaks are plotted against helium fluid temperatures in figure 12. At the minimum fluid temperature of -385° F, the heat leak was 9.8 Btu/hr. The maximum heat leak of 13.4 Btu/hr occurred at -300° F. At the maximum temperature of -125° F the heat leak was 8.3 Btu/hr. The fact that the heat leak decreased as the fluid temperature dropped below -300° F may have been caused by a combination of the following: (1) an improved annulus vacuum as a result of cryopumping by the colder fluid, (2) a decreasing thermal conductivity of the pressure vessel supports and fluid flow tubing, and (3) by a reduction in radiant heat transfer caused by reduced pressure vessel absorptivity and reduced radiation-shield emissivity. At -300° F and above the heat leak decreased. These relationships between heat leak and temperature may be unique for each CSS design. Additional test programs are recommended to better define heat leak as a function of fluid temperature.

#### Test 9 - Pressure Vessel Nonvented Standby Performance With Helium at Maximum Fill of Hydrogen Shroud

The objective of this test was to provide additional information on the nonvented standby performance with helium in the pressure vessel and liquid hydrogen in the shroud. Whereas the test 7 helium-hydrogen nonvented standby test did not include refilling the liquid hydrogen after the start of the test, test 9 included refilling the liquid hydrogen shroud at frequent intervals. Maintaining the shroud fill of liquid hydrogen provided a nearly complete thermal shield for the helium by preventing the heat transfer to the helium pressure vessel through the ullage of a partially filled shroud. Tests 7 and 9 allowed a comparison between shroud fill and nonvented standby time. The procedure consisted of pressurizing the CSS pressure vessel to 500 psig with gaseous helium and then filling the shroud with liquid hydrogen. The helium supply regulator remained in service to add additional helium and to maintain 500 psig as the gaseous helium was cooled to liquid hydrogen temperature. The pressure vessel helium was allowed to reach a thermal equilibrium and the shroud refilled to provide complete cooling of the helium prior to the start of the nonvented standby test. Helium was added until the pressure and fluid density approximated the test 7 starting conditions.

The initial transfer of liquid hydrogen to the shroud began on February 20 at 1400 (0 hours E.T.). The starting pressure of 502 psig and fluid density of 4.63 lb/ft<sup>3</sup> were similar to the nonvented standby phase of test 7. Additional

liquid hydrogen was added to the shroud throughout the test in order to maintain a high percentage of liquid in the shroud. The transfer of liquid hydrogen to the shroud consisted of adding liquid hydrogen through the bottom fill port and continuing the flow until liquid was discharged through the shroud top vent port. The transfer line was chilled before filling the shroud to prevent warming the shroud by excessive gas flow.

Figure 13 illustrates the helium nonvented pressurization for test 9. The times of shroud refills are also noted. The first four additions of liquid hydrogen were at 3-hour intervals, the fifth at a 5-hour interval, the sixth at a 9-hour interval, and the seventh at a 6-hour interval. An initial pressure decay from 502 to 477 psig occurred when the gaseous helium supply was removed for the start of the nonvented standby test. The initial nonvented standby period between shroud hydrogen additions (0.5 to 3 hours E.T.) indicated an 11-psig increase. Each of the following 3-hour intervals indicated smaller pressure increases. The 9-hour interval between shroud hydrogen additions (17.5 to 26 hours E.T.) indicated a 10-psi increase. This should be considered a more reliable indication of pressure increase than the initial 3-hour interval. As shown in figure 13, the minimum helium pressures occurred shortly after completion of the hydrogen transfer. The highest rate of helium pressure increase occurred 1 to 2 hours after addition of liquid hydrogen. The rate of pressurization then decreased.

There was no controlled temperature environment for test 9 as for the preceding eight tests, because the frequent addition of liquid hydrogen required that the test fixture be left open for permanent connection of the hydrogen transfer lines. The ambient temperature ranged from 40° to 59° F. The average hydrogen evaporation rate from 19 through 26 hours E.T. was 0.0364 lb/hr. This 7-hour period was the longest stable evaporation rate due to the frequent refills. Average shroud pressure for this period was 1.082 psig. The average heat leak to shroud over this period was 6.96 Btu/hr. Over this same period vessel pressure increased from 481.9 to 484.0 psig, which indicates a heat leak of 0.1 Btu/hr.

The 0.1 Btu/hr heat leak was indicated between 19 and 26 hours E.T., but test 9 actually had an overall pressure decrease. From an initial pressure of 477 psig at 0.5 hours E.T. the pressure fell to 474 psig following the final shroud fill at 33 hours E.T. This decrease was probably caused by an incomplete temperature equilibrium between the liquid hydrogen shroud and the helium in the pressure vessel before the start of test 9. The additions of hydrogen to the shroud caused the temperature of the helium in the pressure vessel to decrease which subsequently caused a decrease in the pressure of the pressure vessel.

The results of test 9 indicate that a primary cryogen may be maintained for extended periods in a nonvented standby condition by a shrouded CSS if the shroud fluid is maintained at a high percentage fill. A revision of this shroud design is recommended which would decrease the sensitivity of the pressure vessel thermal performance to the liquid level in the shroud.

## CONCLUSIONS AND RECOMMENDATIONS

1. The integral shroud design is capable of maintaining a primary cryogen in a nonvented standby condition for extended periods if the shroud liquid is maintained at a high percentage fill.

2. It is recommended that the shroud design be revised to decrease the sensitivity of pressure vessel thermal performance to the shroud liquid level.

3. The integral shrouded CSS indicated a heat leak as low as 0.1 Btu/hr during a period of maximum shroud fill.

4. The capacitance quantity gaging system did not have sufficient range for helium to provide useful fluid density data.

5. A shroud fluid quantity gaging system is desirable.

6. Preliminary investigation indicates that the maximum heat leak to the CSS pressure vessel (shroud empty) with helium occurred at a fluid temperature of  $-300^{\circ}$  F. A decreasing heat leak occurred as fluid temperature increased or decreased from  $-300^{\circ}$  F. It is recommended that additional tests be conducted to better define CSS thermal performance as a function of fluid temperature.

7. In this CSS heater configuration, significant fluid stratification was indicated by pressure decays following heater deactivation. The fluid stratification was caused by an inoperative antistratification fan motor.

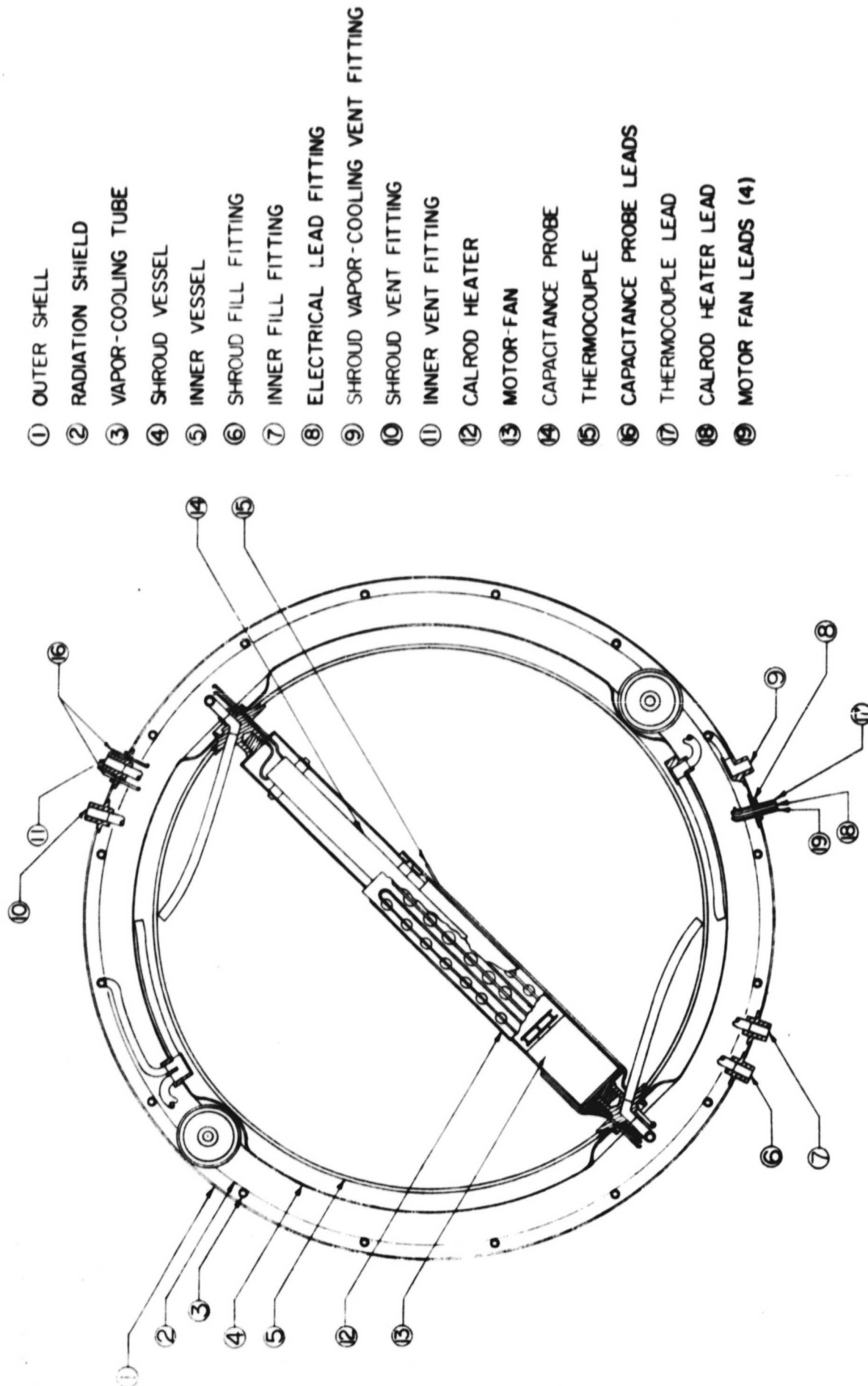


Figure 1.- Schematic diagram of liquid shrouded CSS.

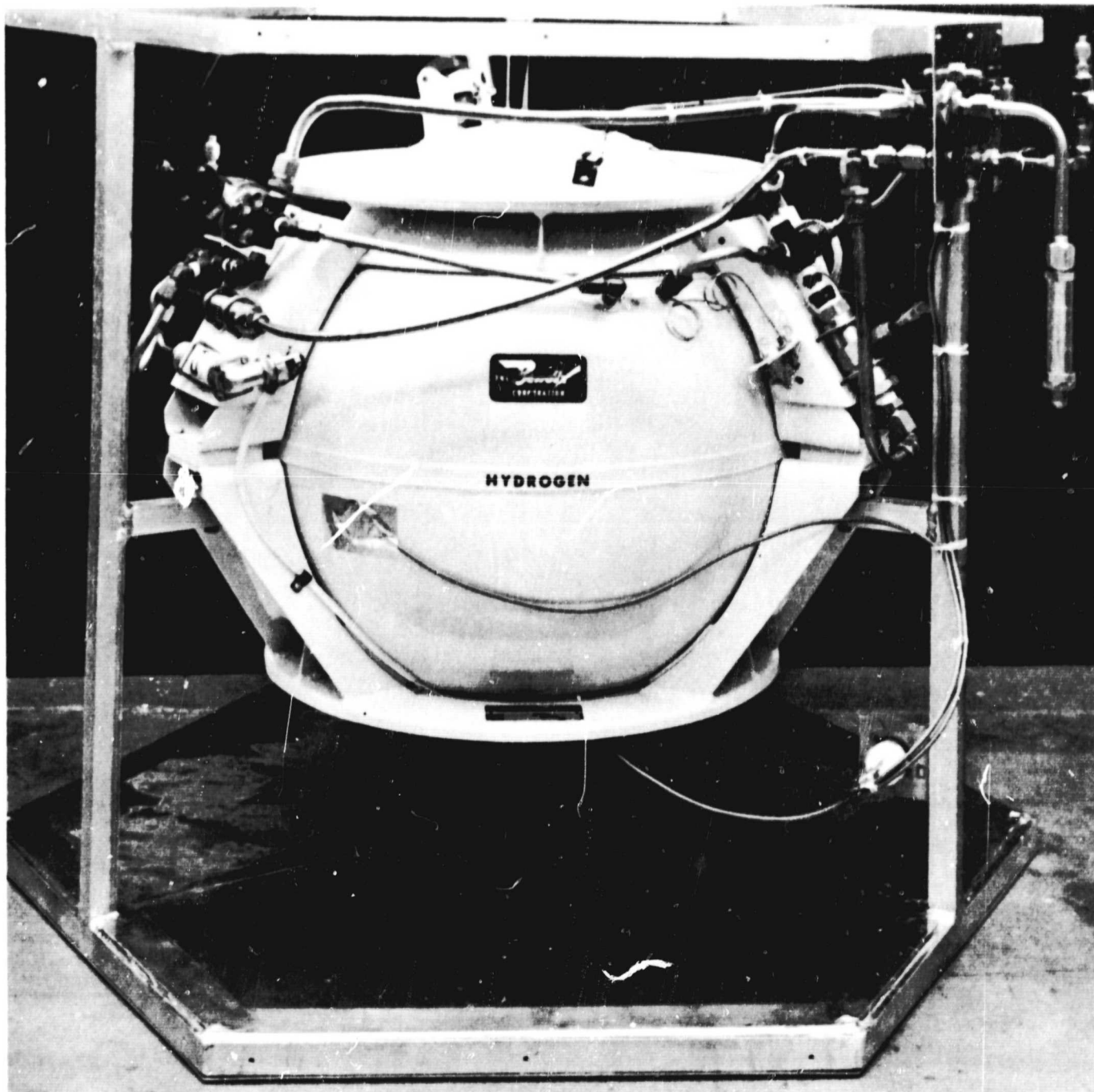


Figure 2.- Liquid shrouded CSS in support fixture.

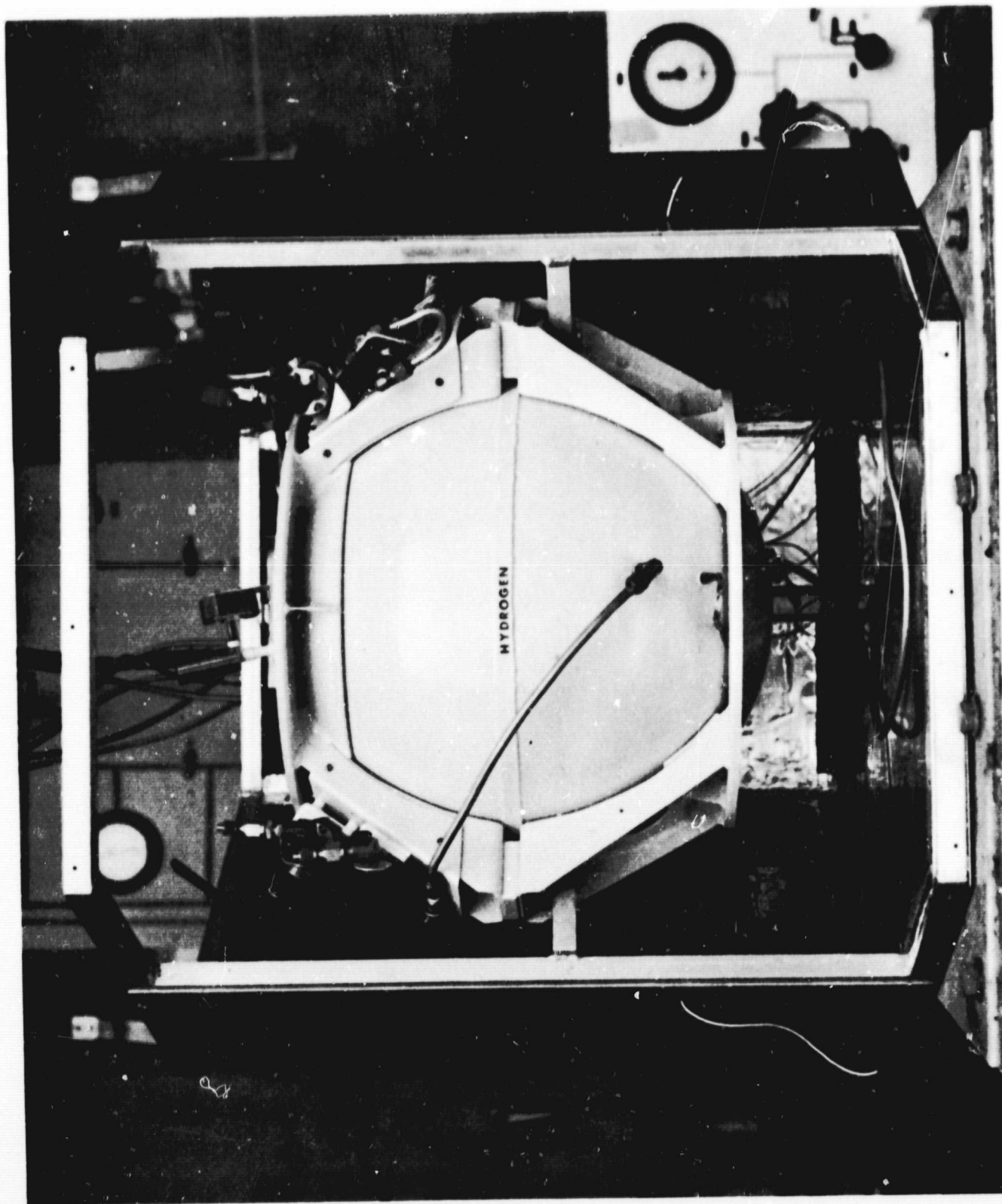


Figure 3.- Liquid shrouded CSS in insulated test fixture.

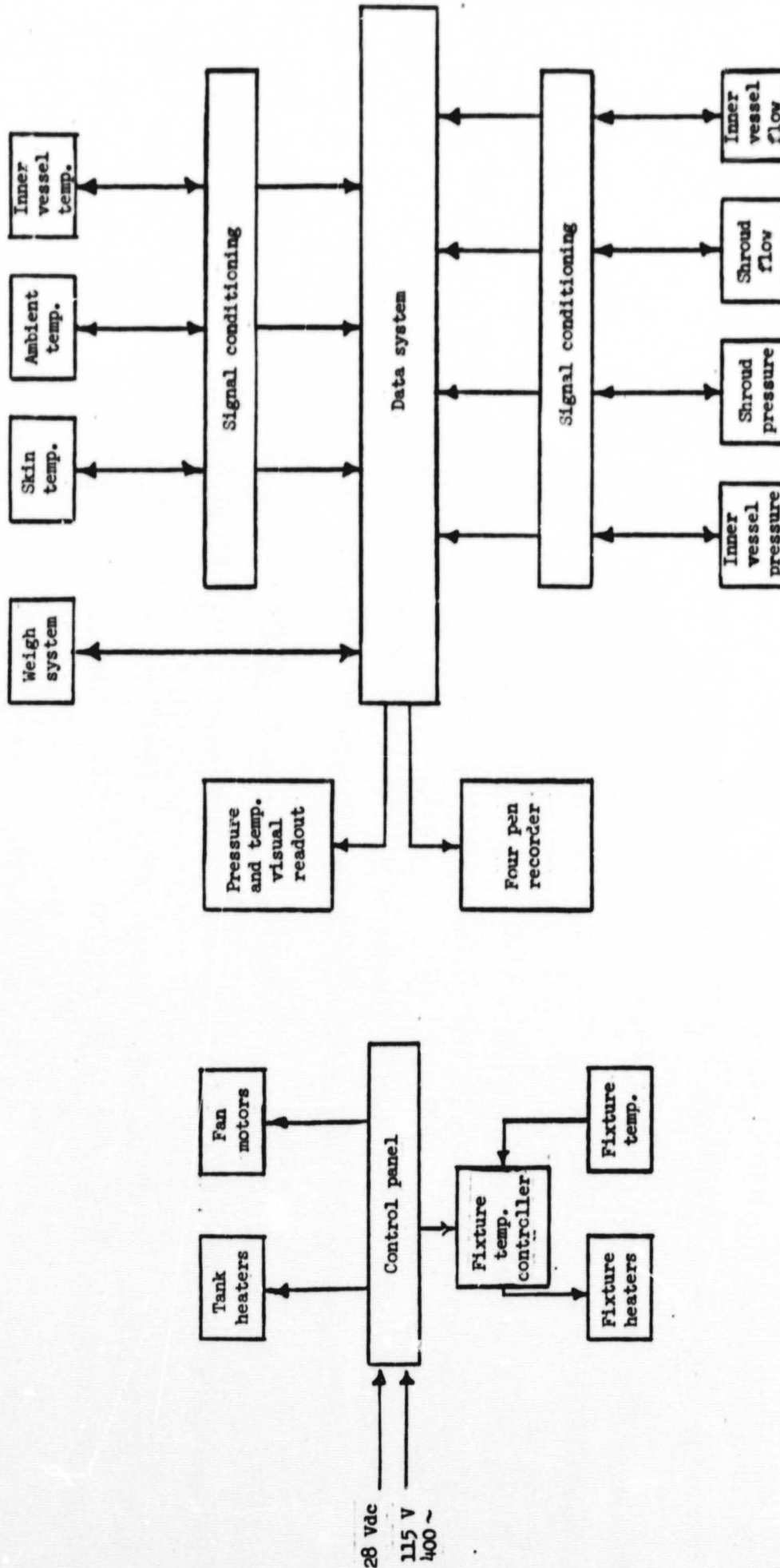


Figure 4.- Fluid flow schematic.

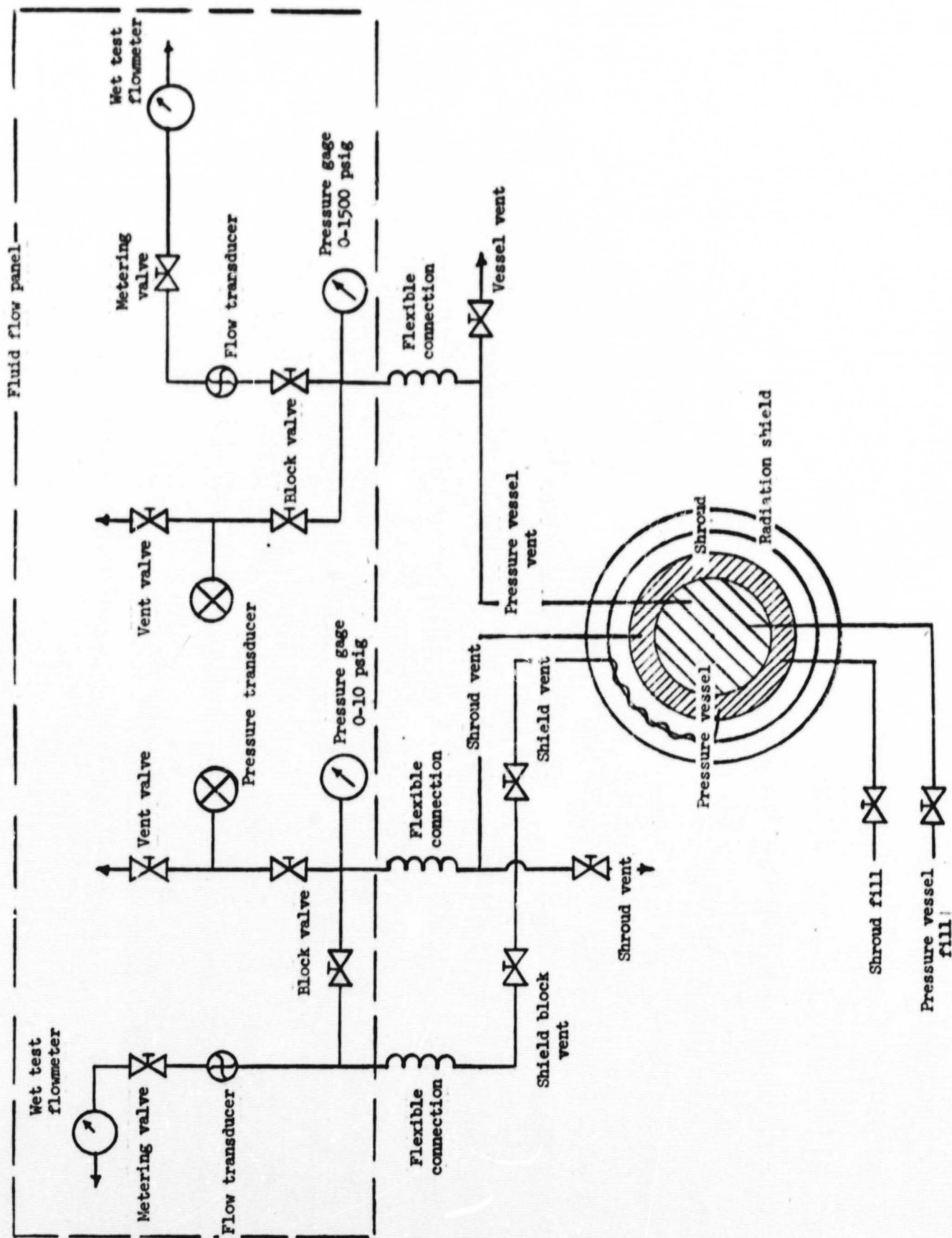


Figure 5.- Instrumentation block diagram.

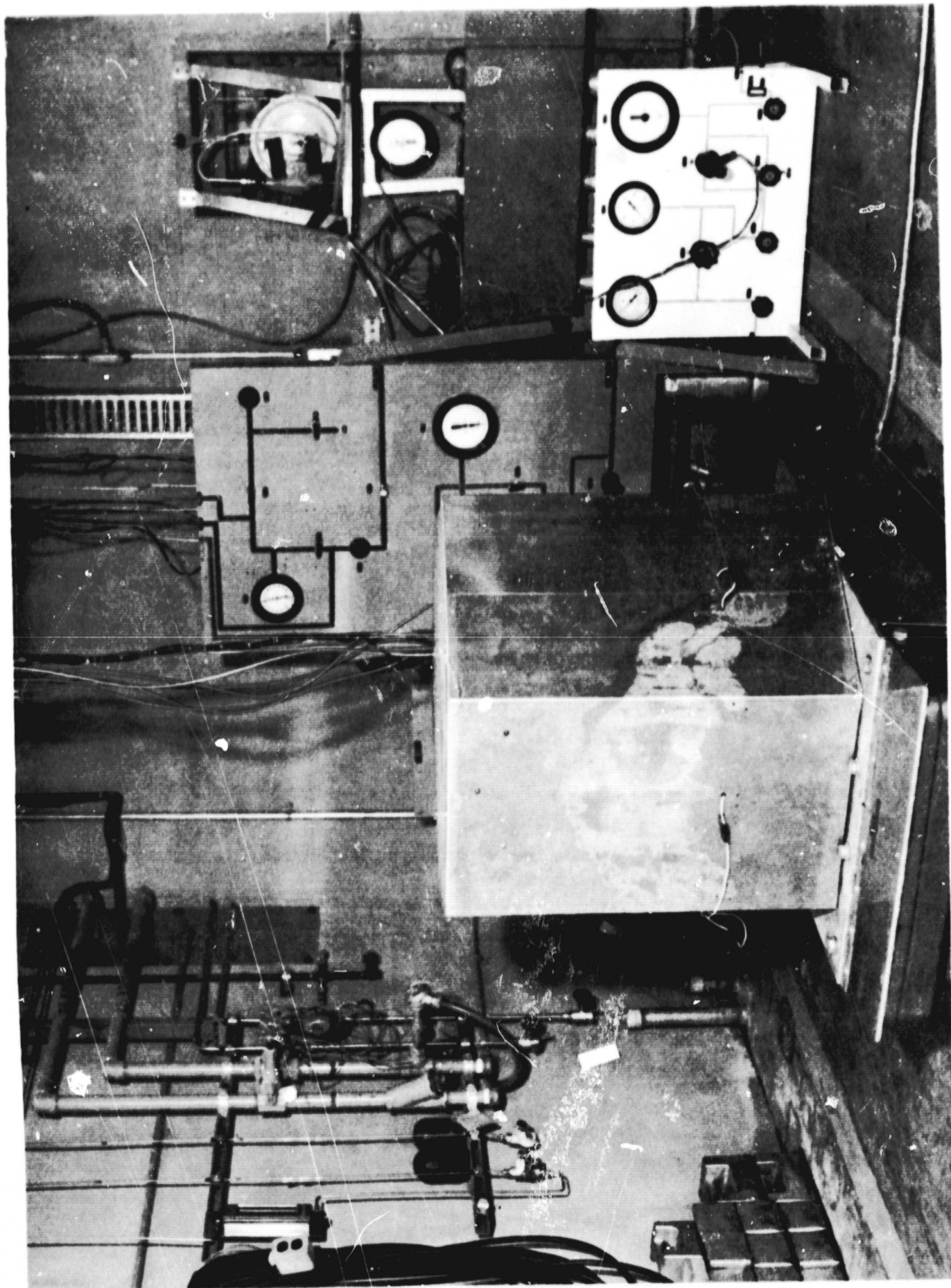


Figure 6.- Liquid shrouded CSS test setup.

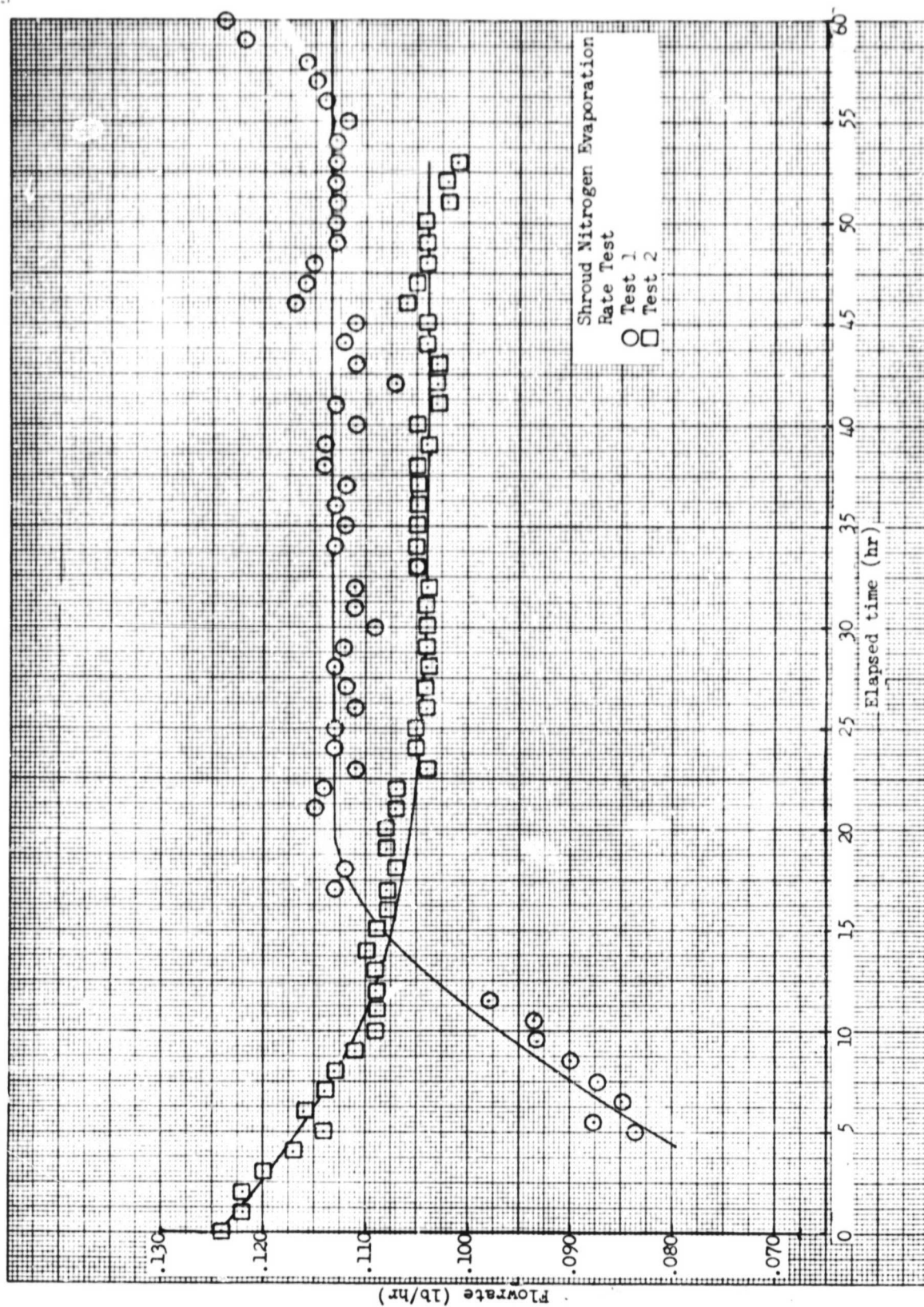


Figure 7.- Shroud nitrogen evaporation rate - tests 1 and 2.

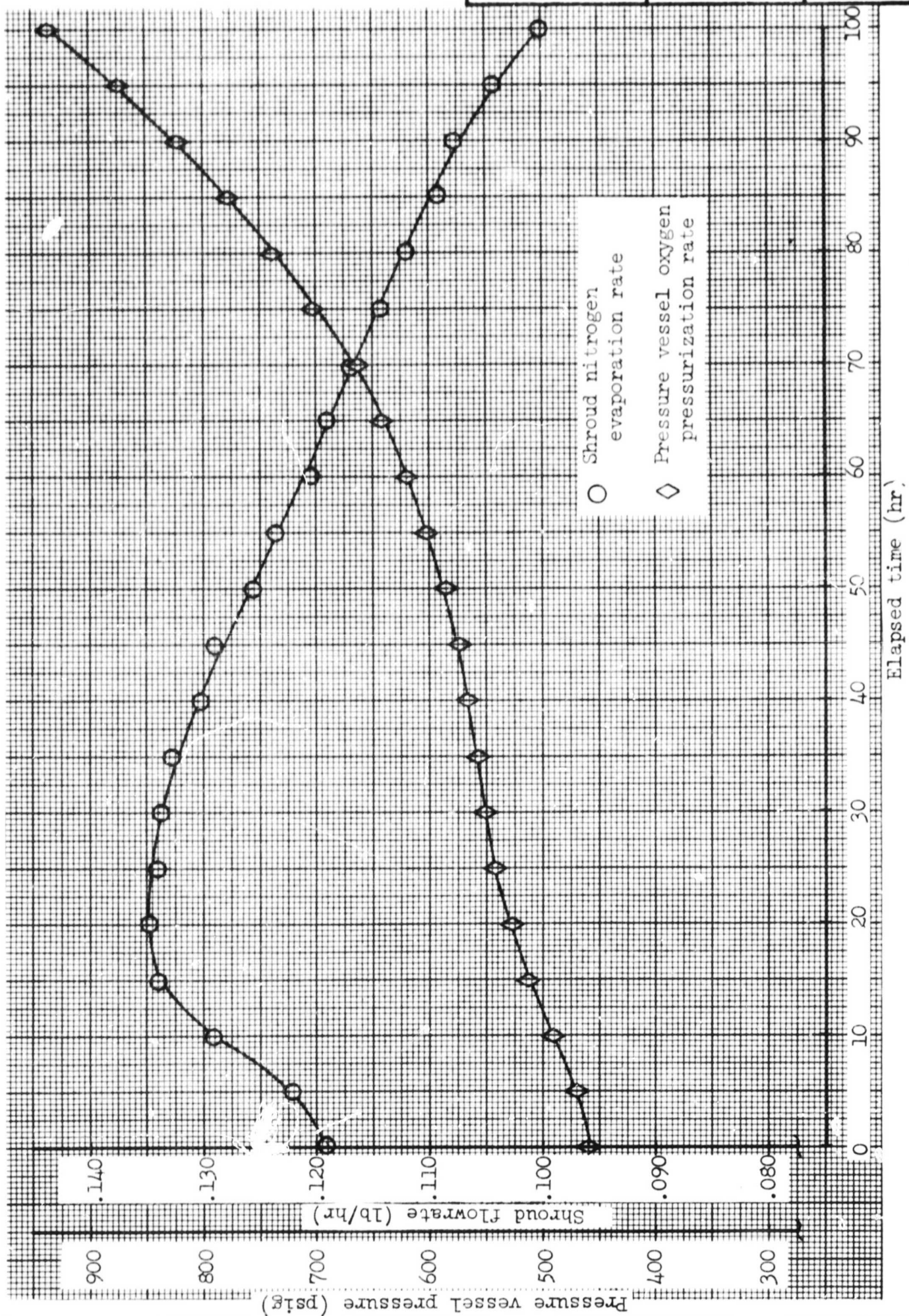


Figure 8.- Shroud nitrogen evaporation rate and pressure vessel oxygen nonvented standby pressurization - test 3.

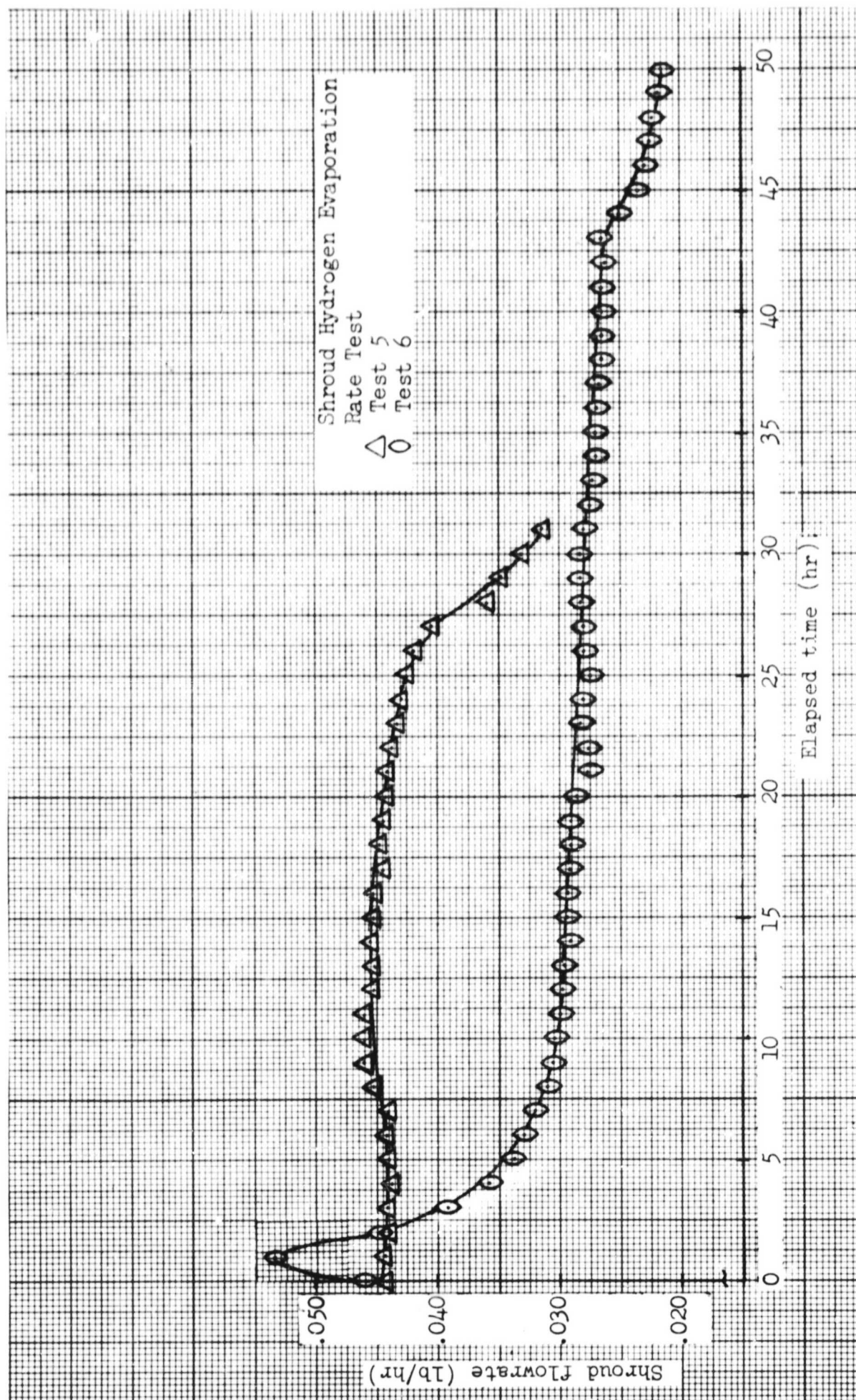


Figure 9.- Shroud hydrogen evaporation rate - tests 5 and 6.

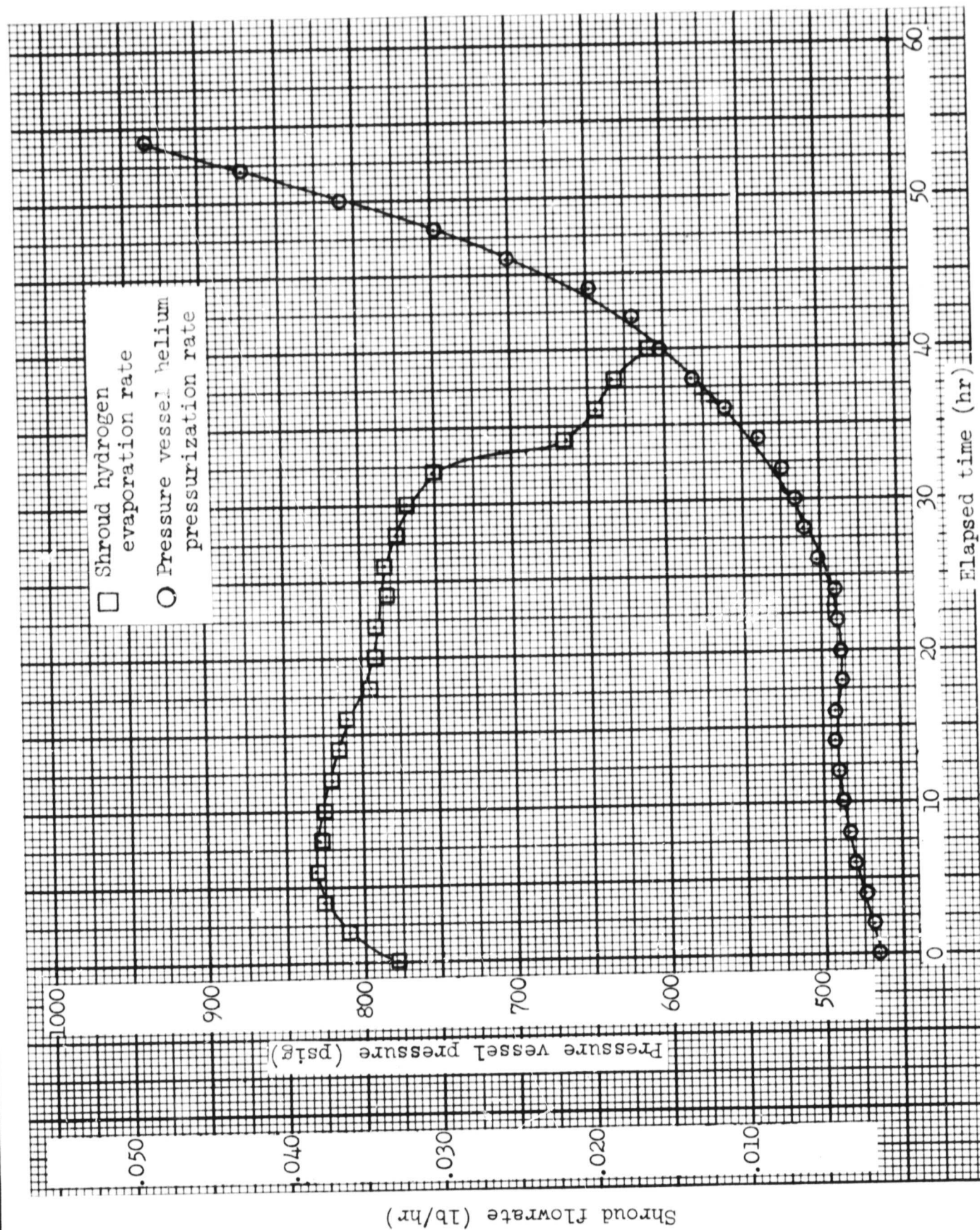


Figure 10.- Shroud hydrogen evaporation rate and pressure vessel helium nonvented standby pressurization - test 7.

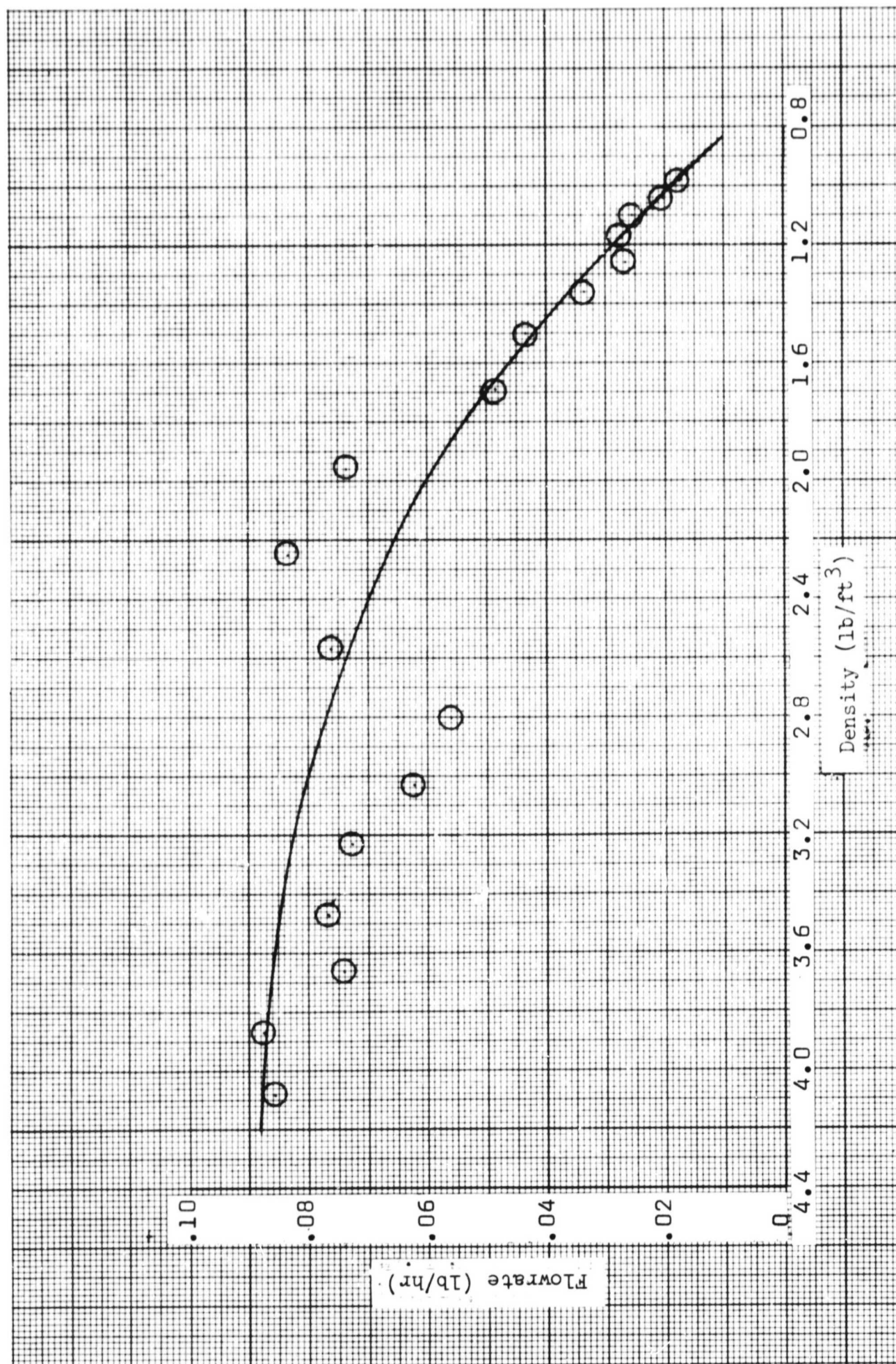


Figure 11.- Pressure vessel helium flowrate versus fluid density - test 8.

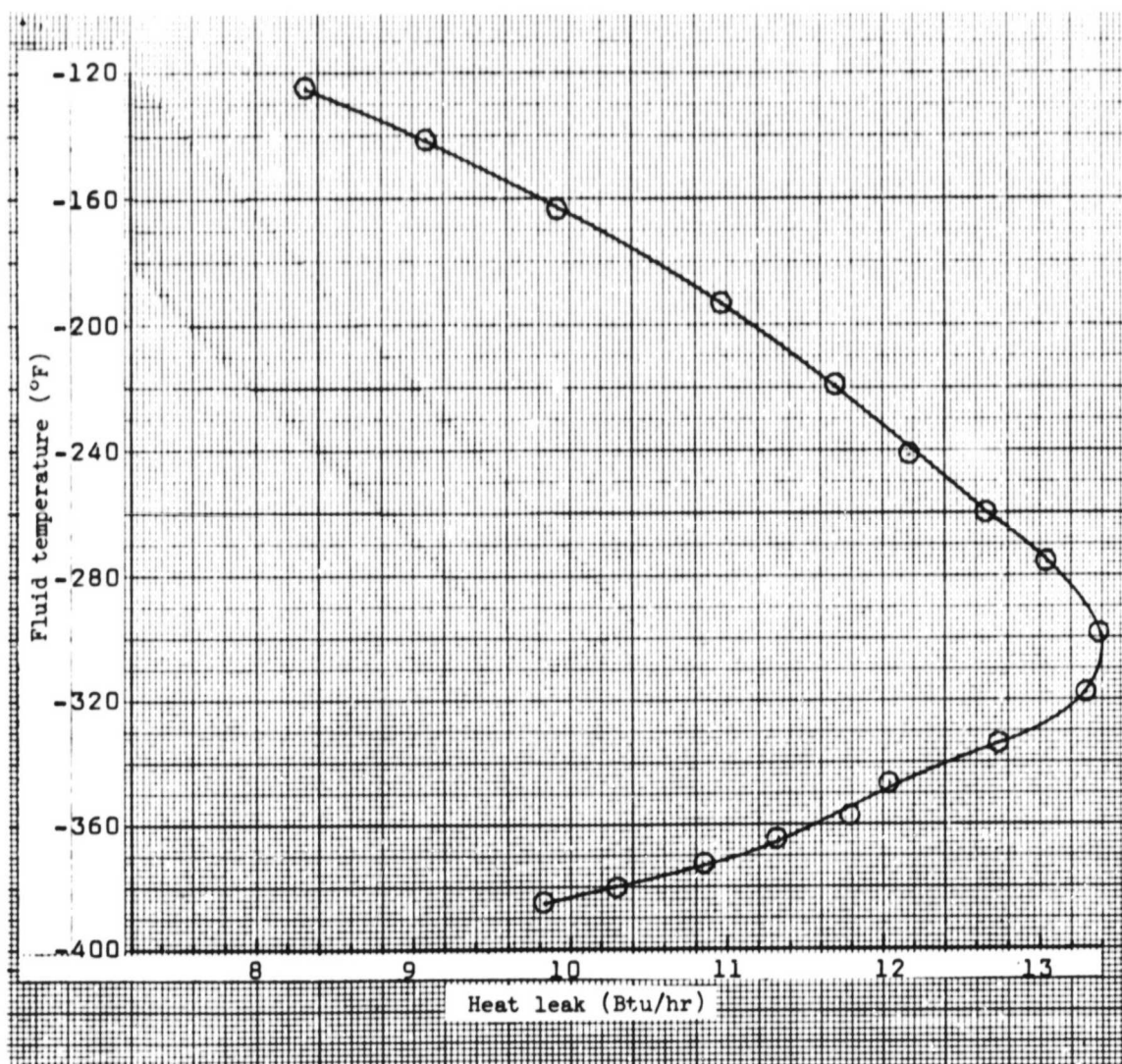


Figure 12.- Heat leak versus helium fluid temperatures - test 8.

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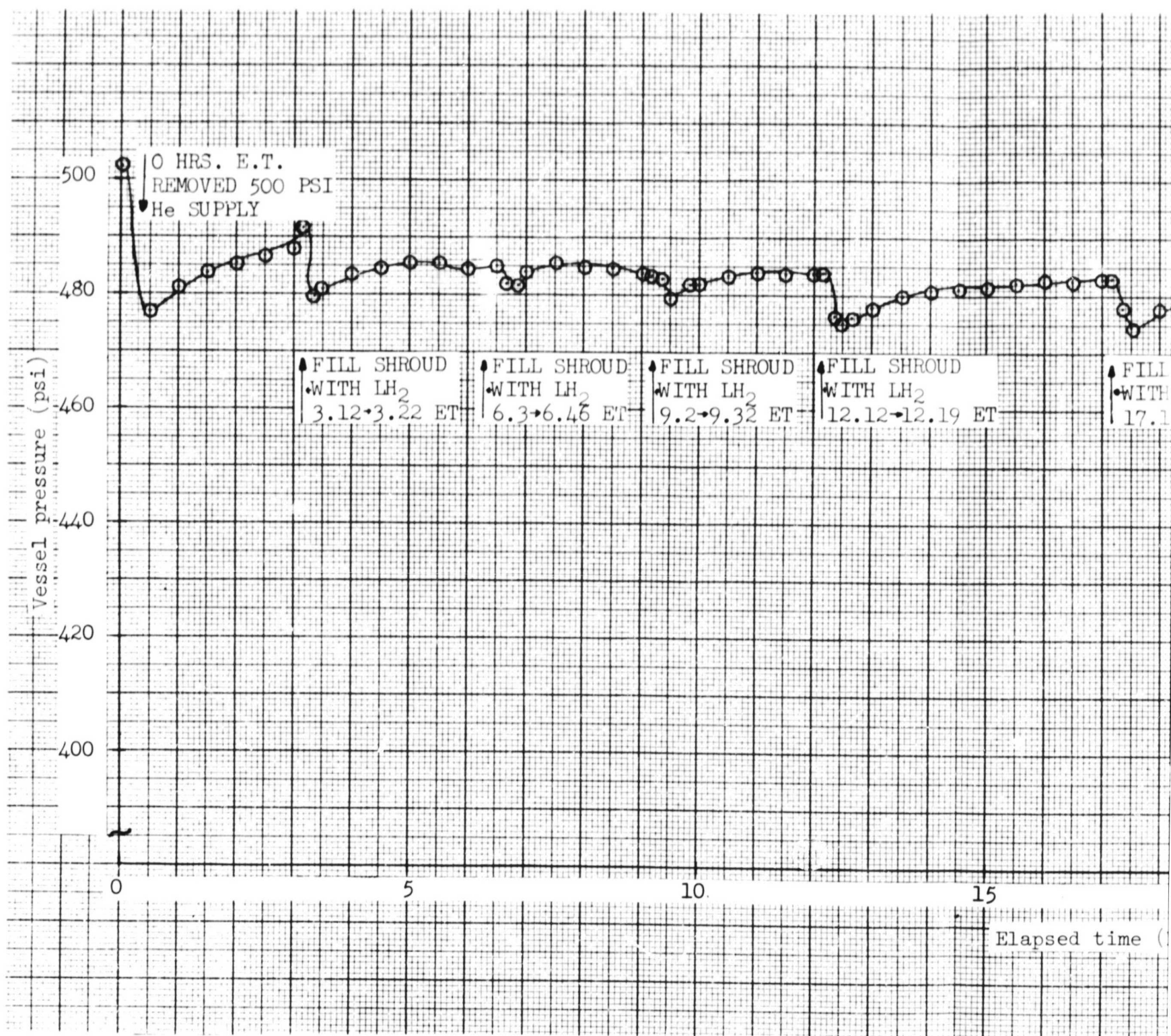
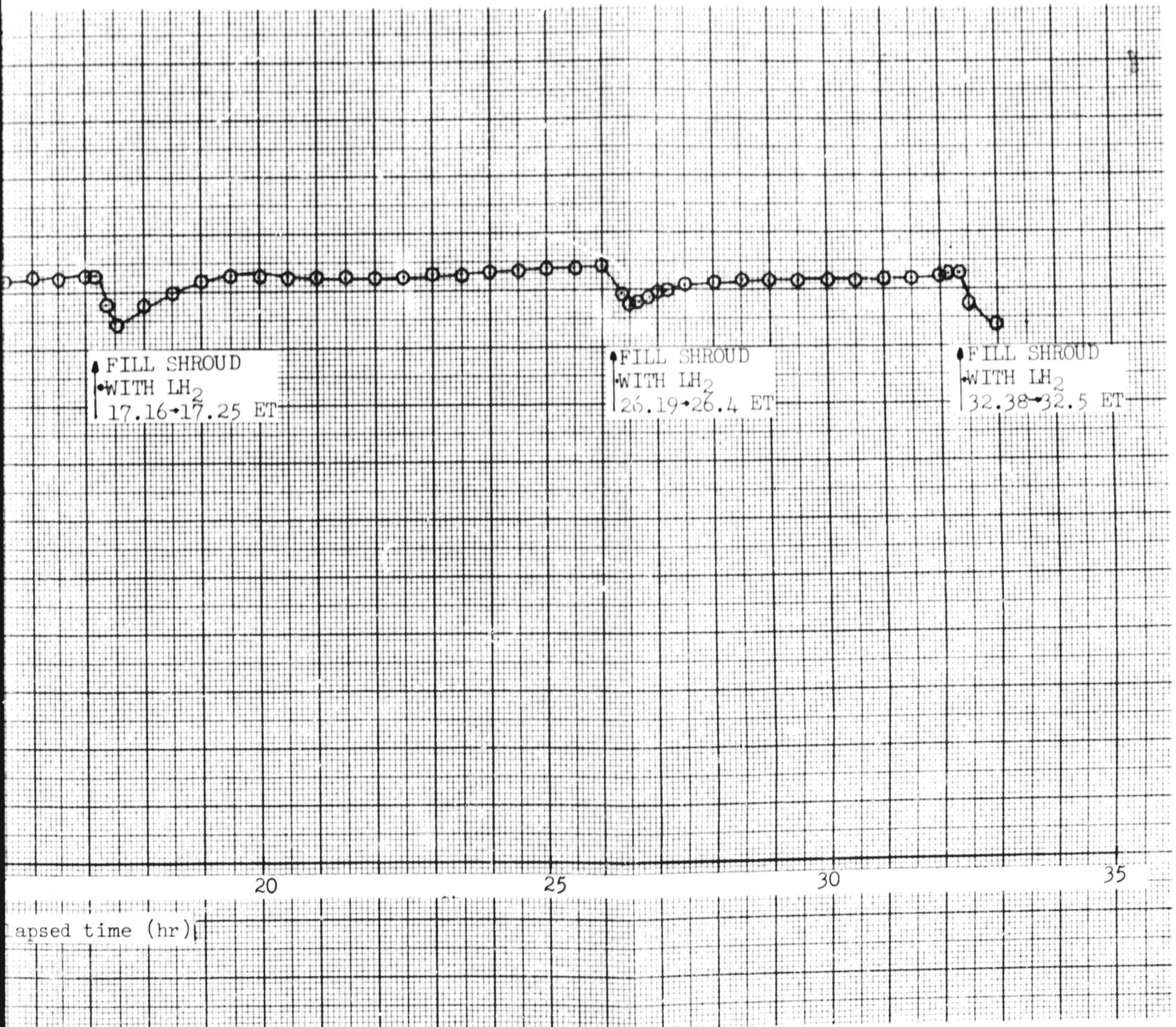


Figure 13.- Helium nonvented s

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am nonvented standby test - test 9.